



ONR FINAL REPORT FOR CONTRACT #N00014-90-J1029

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This contract started in October, 1989 and continued through March 1992, which included a half-year extension. The overall purpose of the contract was to investigate various aspects of the quantum theory of multiwave mixing with applications to squeezing in both atomic and semiconductor media. In the following seven sections, we briefly describe what we have achieved with help from the ONR contract in these and related areas. We also list the corresponding papers presented at meetings, the papers published in journals, and the work completed on two books.

1. Injected Atomic Coherence

In nonlinear spectroscopy and in laser theory, atoms are usually pumped incoherently, that is, any induced dipole moment is destroyed by the pumping process. Recently substantial interest in both micromasers and in correlated emission lasers has involved pumping in which induced dipoles are preserved. We have studied the effects of such injected atomic coherence on multiwave mixing processes and in a simple two-level laser. In particular, we have found that laser operation can occur way below the usual laser threshold and that below that threshold, the output field is always locked to the injected atomic coherence. While this result is pretty, we note that in general lasing without inversion is not particularly surprising. The gain is in the first instance proportional to the imaginary part of the induced polarization; with the right phase, you get gain. An inversion is only one way to ensure that you get the right phase, albeit a very good way.

2. Bichromatic and Local-Field-Correction Quantum Multiwave Mixing

The proposed work on bichromatic multiwave mixing was carried out analytically, but never reached publication, partly because some good work on part of the problem appeared, namely in resonance fluorescence. The corresponding squeezing coefficients (C_1 and D_1) still remain to be worked out in the literature.

We have worked out the quantum theory of multiwave mixing with local field corrections, including a first-principles derivation of the Maxwell-Bloch equations starting with a basic minimal coupling Hamiltonian in the Coulomb gauge. This work will be submitted for publication in the first quarter of 1993.

3. Composite-Cavity Mode Laser

We have presented and published work on the composite cavity-mode approach to reflections by a external mirror. This reveals a very sensitive dependence on the length of the external cavity and might explain some experimental behavior that is currently attributed to chaos [see Rose *et al* (1992)]. This work is aimed at instability problems in semiconductor lasers, but the model should be useful for coupled lasers with two-level gain media as well.

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4. Spectral Hole Burning and Population Pulsations in SCL Gain Media

This work studied hole burning and population pulsations in semiconductor gain media and related phenomena. We made substantial progress in this area, notably in being able to derive a general multiwave mixing formalism that treats the many-body quasiequilibrium semiconductor as well as simpler models with a unified notation. The trick was to express the mixing coefficients in terms of the single-mode susceptibility, which then encapsulates the model in question. This simple form reveals similarities and differences between multiwave mixing in a variety of media, and allows us to interpret the popular linewidth enhancement factor as the ratio of the imaginary to real parts of the mode coupling coefficient.

A related approach has enabled us to derive a multimode theory of the quasiequilibrium laser. This is limited to weak laser fields, but can describe the full many-body effects. Nevertheless, the theory is actually simpler than the original Lamb theory of the gas laser [see Sargent (1993)].

5. Quantum Multiwave Mixing in Semiconductor Laser Media

We have published a number of papers on the quantum theory of multiwave mixing in semiconductor media and found coherent-dip phenomena reminiscent of detuned two-level media with population-difference decay times (T_1) much larger than the dipole decay time (T_2). Some of this work has led to a more precise understanding of just when a simple two-level model has a chance of applying to a semiconductor and when it is likely to fail. As discussed in the SCL book and in the most recent OSA talk, the simplest two-band semiconductor model actually has four levels for each momentum-spin combination, two of which correspond to the two levels in a two-level system. Carrier-carrier scattering causes all four levels to have appreciable probability in a semiconductor gain medium. Hence it is dangerous to use a two-level model to describe even the simplest of semiconductors. It is particularly unwise, since a simple semiconductor theory often reduces to the solution of a few equations. Exceptions occur when the many-body effects of Coulomb enhancement and band-gap renormalization are included, or in the quantum theory of the semiconductor. One may curve fit some phenomena using such two-level models, since for small variations of parameters, the semiconductor characteristics are reasonably slowly varying that first and second-order Taylor series are good approximations.

6. Semiconductor Laser Photon Statistics

The SCL photon statistics is an important problem, since aside from the intrinsic interest about photon statistics, this area might help to explain the intensity squeezing observed by Yamamoto and others. The current theories are either based on a simple two-level model, or on circuit theory analogs. We have developed a joint photon/carrier-density statistics, p_{nN} , where n is the photon number and N is the carrier number. This approach leads to an intricate 2D set of equations. In the limit that the carrier number is exactly related to the photon number (via saturation), the two-dimensional space reduces to a one dimensional one similar to that for two-level media. In general, no such simple relationship exists in the semiconductor, since the saturation changes the chemical potential, which in turn changes the Fermi-Dirac distributions functions. These distributions are already traces over the original semiconductor-field probability functions, traces that destroy a simple relationship between semiconductor-field probabilities and a single photon number.

Nevertheless, we have recently found that the simple upper-to-ground-level two-level model predicts much of the thresholdless laser operation observed in laser diode structures that confine spontaneous emission to the laser axis.

7. Semiconductor Laser Linewidth

We have studied the SCL linewidth, including a complete derivation of the quantum-Langevin diffusion coefficients. This derivation will be given in our forthcoming book on *Semiconductor Laser Physics*. Several surprises have occurred, since no one seems that have done a first-principles derivation. Typically the diffusion coefficients reported in the literature were either adopted from the two-level theory or were intuited from circuit-theory analogs. At this point, the differences in the final answers do not appear to be large, and in any event have not been checked against controlled experiments.

8. Books

Much of the work related to semiconductor lasers has been incorporated into a draft of our forthcoming book W. W. Chow, S. W. Koch, and M. Sargent III, *Semiconductor Laser Physics*. With regard to books, we produced the second edition of the book *Elements of Quantum Optics*. This edition includes many new figures, corrections, and new sections on the relationship between four-wave mixing and photon echo, on light forces and atomic motion, and on the quantization of standing waves versus traveling waves. The first edition of this book was created with significant support from earlier ONR contracts.

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Students and Post Docs supported

SungYuck An, Tim Carty, Mike Rose, Paul Gohman

Talks Presented

S. W. Koch, H. Haug, M. Sargent III, and N. Peyghambarian, "Optical Nonlinearities in Bulk and Quantum-Well Semiconductors and Semiconductor Quantum Dots," Fifth Interdisciplinary Laser Science Conference (ILS-V) (1989) (invited).

T. Carty and M. Sargent III, "Frequency Locking of a Laser by Injected Atomic Coherence," OSA Annual Meeting, 1989 Technical Digest Series Vol. 18 (Optical Society of America, Washington, DC), 72 (1989).

M. Sargent III, "Multiwave Mixing in Semiconductor Media," LASERS '89 (1989) (invited).

M. Sargent III, "Lasing without Inversion," 20th Winter Colloquium on Quantum Electronics, Snowbird, January (1990) (invited).

M. Sargent III, S. W. Koch, and W. W. Chow, "Theory of a Semiconductor Laser," SPIE Conference on Nonlinear Optical Materials and Devices for Photonic Switching, Los Angeles (1990) (invited).

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M. Sargent III, S. W. Koch, and W. W. Chow, "Theory of a Single-Mode Semiconductor Laser," Meeting on Space-Time Complexity in Nonlinear Optics, Tucson, AZ, March 12-16 (1990).

W. W. Chow, S. W. Koch, and M. Sargent III, "Effects of electron-hole Coulomb interaction in semiconductor lasers," IQEC '90, Technical Digest Series 8, 208 (1990).

M. Sargent III, S. W. Koch, and W. W. Chow, "Onset of sidemode buildup in semiconductor lasers," IQEC '90, Technical Digest Series 8, 204 (1990).

M. Sargent III, "Role of Population Pulsations and Hole Burning in Multimode Semiconductor Laser Operation," 1990 Aspen Workshop on *Physics of Semiconductor Lasers*, Aspen, CO (1990) (Program Chairman).

M. Sargent III, "Spectral Hole Burning in Semiconductor Lasers," 21th Winter Colloquium on Quantum Electronics, Snowbird, January (1991) (invited).

M. Lindberg, M. Rose, W. Chow, M. Sargent III, and S.W. Koch, "Theory of Semiconductor Laser Feedback Instability", paper CTuJ2, Conference on Lasers and Electro-Optics CLEO'91, Baltimore, MA, May 12 - 17, (1991).

M. Sargent III, S. W. Koch, and W. W. Chow, "Sidemode Gain in Semiconductor Lasers", OSA annual meeting, San José (1991).

M. Sargent III, S. An, and J. E. Sipe, "Quantum Multiwave Mixing with a Local Field Correction, OSA annual meeting, San José (1991).

M. Sargent III, "Multiwave Mixing in Semiconductor Media," 22th Winter Colloquium on Quantum Electronics, Snowbird, January (1992) (invited).

M. Sargent III, A. Mufti, H. Schmidt, B. Balantekin, "Simple applications of Lie algebras to quantum optics," 22th Winter Colloquium on Quantum Electronics, Snowbird, January (1992).

M. Sargent III, "Hole Burning and Population Pulsations in Semiconductor Laser Media," SPIE *Compound Semiconductor Physics and Devices* Somerset, N.J. (1992) (invited and Program Cochair).

M. H. Rose, W. W. Chow, S. W. Koch, M. Lindberg, and M. Sargent III, "Dynamics of a Coupled-Cavity Semiconductor Laser", IQEC, Vienna (1992).

A. Mufti, H. A. Schmitt, A. B. Balantekin, and M. Sargent III, "Analytic Solution to a Damped Harmonic Oscillator Master Equation," IQEC, Vienna (1992).

M. Sargent III, "Nearly Degenerate Multiwave Mixing in Two-Level Atoms and in Quasiequilibrium Semiconductors," IQEC, Vienna (1992).

R. Jin, D. Boggavarapu, J. Grantham, Y. Hu, H. M. Gibbs, G. Khitrova, S. W. Koch, M. Sargent III, F. Brown de Colstoun, and C. Lowry, "Dynamics of a microcavity laser with optical injection," OSA Annual Meeting, Albuquerque, NM (1992).

M. Sargent III, "Limitations of two-level models in semiconductor gain media," OSA Annual Meeting, Albuquerque, NM (1992).

Papers published or submitted

S. An and M. Sargent III, "Quantum Theory of Multiwave Mixing. X. Two-Photon Three-Level Model," *Phys. Rev. A* **39**, 1841 (1989).

S. An and M. Sargent III, "Theory of Multiwave Mixing in a Squeezed Vacuum," *Phys. Rev. A* **39**, 3998 (1989).

S. An and M. Sargent III, "Quantum Theory of Multiwave Mixing. XI. Effects of Sidemode Saturation," *Phys. Rev. A* **40**, 795 (1989).

M. Sargent III, F. Zhou, S. An, M. Lindberg, and S. W. Koch, "Theory of a Semiconductor Laser," in *Proceedings of the Vth International Symposium on Quantum Optics*, Ed. by D. F. Walls and J. D. Harvey, Springer-Verlag, Berlin (1989).

S. W. Koch, H. Haug, C. Ell, M. Lindberg, and M. Sargent III, "Many-Body Theory of the Electron-Hole Plasma in Bulk and Quantum-Well Semiconductor Lasers," in *Proceedings of the Vth International Symposium on Quantum Optics*, Ed. by D. F. Walls and J. D. Harvey, Springer-Verlag, Berlin (1989).

M. Lindberg, S. An, S. W. Koch, and M. Sargent III, "Strong-Field Modulation of Semiconductor Luminescence Spectra," *Phys. Rev. A* **40**, 4415 (1989).

S. An and M. Sargent III, "Quantum Theory of Multiwave Mixing. Squeezed Vacuum Model," *Phys. Rev. A* **40**, 7039 (1989).

F. L. Zhou, M. Sargent III, and S. W. Koch, "Generation of Population Pulsations and Sidemodes in Semiconductor Media," *Phys. Rev. A* **41**, 463 (1990).

T. Carty and M. Sargent III, "Frequency Locking of a Laser by Injected Atomic Coherence," *Opt. Lett.* **15**, 57 (1990).

S. An and M. Sargent III, "Enhanced Squeezing in a Squeezed Vacuum," *Opt. Lett.* **15**, 139 (1990).

M. Sargent III, S. W. Koch, and W. W. Chow, "Theory of a Semiconductor Laser," *SPIE Vol. 1216 Nonlinear Optical Materials and Devices for Photonic Switching*, p. 130 (1990) (invited).

M. Sargent III, Electronic Information column, *Optics & Photonics News* **1**, 54 (1990).

T. Carty and M. Sargent III, "Effects of Injected Atomic Coherence on One-Photon Single-Mode Interactions," *Phys. Rev. A* **42**, 1532 (1990).

T. Carty and M. Sargent III, "Effects of Injected Atomic Coherence on Single-Mode Frequency Locking in a Cavity," to be published in *Phys. Rev. A* **42**, 1544 (1990).

A. Paul, S. An, M. Lindberg, S. W. Koch, and M. Sargent III, "Squeezing in Quasi-Equilibrium Semiconductor Media," *Phys. Rev. A* **42**, 1725 (1990).

W. W. Chow, S. W. Koch, and M. Sargent III, "The Effects of Electron-Hole Coulomb Interaction in Semiconductor Lasers," *IEEE J. Quantum Electronics* **26**, 1052 (1990).

W. W. Chow, S. W. Koch, M. Sargent III, and C. Ell, "Many-Body Effects on the Linewidth Enhancement Factor in Quantum-Well Lasers," *Appl. Phys. Lett.* **58**, 328 (1991).

M. Sargent III, "Hole burning and population pulsations in semiconductor laser media," *SPIE Vol. xxx Compound Semiconductor Physics and Devices*, p. (1992) (invited).

A. Mufti, H. A. Schmitt, and M. Sargent III, "Finite-dimensional matrix representations as calculational tools in quantum optics," *Am. J. Phys.*, to be published.

M. Sargent III, S. W. Koch, W. W. Chow, "Sidemode gain in semiconductor lasers," *J. Opt. Soc. Am. B9*, (1992).

M. H. Rose, M. Lindberg, W. W. Chow, S. W. Koch, and M. Sargent III, "Composite-cavity-mode approach to single-mode semiconductor laser feedback instabilities," *Phys. Rev. A46*, 603 (1992).

M. H. Rose, M. Lindberg, W. W. Chow, S. W. Koch, and M. Sargent III, "Dynamics of a Composite-Cavity Semiconductor Laser," submitted to *Opt. Lett.*

M. Sargent III, "Theory of a Multimode Quasiequilibrium Semiconductor Laser," to be published in *Phys. Rev. A* (1993).

M. Sargent III, A. Paul, and S. W. Koch, "Nearly Degenerate Multiwave Mixing in Quasiequilibrium Semiconductors," submitted to *Opt. Lett.*

A. Mufti, H. A. Schmitt, A. B. Balantekin, and M. Sargent III, "Analytical Solution to the Master Equation for a Quantized Cavity Mode," submitted to *JOSA B*.